Mechanical Characterization and Improvement of Weaveability for Glass/Polypropylene Commingled Hybrid Yarns

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Abstract-**This study was conducted due to the necessity for improving the processability of commingled yarns during textile processing, in particular dense 3D preform weaving. Open structure of the commingled yarns caused higher production stops. As a possible solution, Glass/Polypropylene (GF/PP) commingled yarns with different twisting levels were produced. Effect of twisting on the mechanical properties of commingled yarns and on their compression molded UD composites are determined. As a result, twisting did not significantly affect the modulus of elasticity of UD-composites. However, the tensile strength of UD-composites was reduced by further processing even without twisting. Therefore small twisting levels can be applied on commingled yarns to improve processability of dense preforms without significantly affecting the mechanical performance. Furthermore, the damage on the yarns, preforms and composites is determined for various weft densities which indicate differing crimp ratios. Higher crimp ratios both increase the damage on reinforcement yarns and significantly decrease the mechanical properties.**

***Keywords*- Hybrid Yarn; Thermoplastic Composite; Woven Preform**

I. INTRODUCTION

Thermoset polymers have been dominating the market as the matrix of choice for composites. Thermosets have lower viscosity in comparison with thermoplastics, which can be seen as the main advantage for the sake of processability. They also do not necessarily need pressure or heat during processing. Thermoset resins are generally inexpensive and stronger than thermoplastics with a higher serving temperature. Short workable pot life, the difficulties concerning the recycling issues and emission of volatile organic compounds are the main disadvantages. Thermoplastics offer higher impact strength and a good surface finish. They can be processed without emission of hazardous gases and recycled much easier [1], [2]. Recycling is becoming more and more important due to the strict regulations of mass production industries such as automobile industry.

The viscosities of fully polymerized thermoplastics are around two to three orders of magnitude higher than their thermoset counterparts [3]. In order to overcome the difficulties of impregnation caused by high viscosity of thermoplastics, reinforcement materials (e.g. carbon, glass) and thermoplastic polymer (e.g. PP, PEEK) are already mixed in solid state. The aim of solid state mixing is to reduce the flow path of polymers during impregnation. This mixture is processed into preforms mostly with textile machinery. Thermoplastic polymers in the preform are melted under the application of pressure and temperature (e.g. pultrusion, compression molding), and consolidated [4]-[6].

Commingled yarns can be produced with a modified air-jet texturizing machine (Fig. 1). The most important modification is the type of air nozzle used. Commercial air nozzles are available, which claim to reduce the damage on the reinforcement yarns during processing and offer a better mixture in the crosssection. Especially for commingled yarns, a good mixture in the crosssection is crucial, because the main idea of commingling process is to reduce the flow paths of the viscous thermoplastic resin. Another important modification for commingling process is the bobbin winding device. Commingled yarns should be wound up with a constant yarn tension with higher bending radii of machine elements to minimize the damage on the yarn. Besides material mixing and high production rates, commingled yarns embody structural elongation which enables a smoother processing with textile machinery. During commingling process, reinforcement yarns are damaged by the applied air pressure in the nozzle, which can be seen as a drawback. Another disadvantage of commingled yarns was identified from processing point of view while executing trials on high packing densities of 3D near-net shape woven preforms [7]-[9]. Harnesses apply forces on the warp yarns in both normal and longitudinal direction during weaving. These forces should be minimized by reducing the warp yarn tension especially for the brittle reinforcement yarns. However, reduced warp yarn tension with high packing density increases the probability of stuck yarns in the shed and causes unclear shed opening. After commingling, yarns become more voluminous and open. Depending on the structure, high packing density commingled yarns showed higher production stops than conventional materials, which necessitates improvement for the industrial production. According to Lee et al. [10] and Rudov-Clark et al. [11], the fibre damage in the weaving process, due to elongation and yarn friction, has only a low impact on the properties of stiffness and strength in the composite. However, the unclear shed opening and resulting machine stops were not discussed.

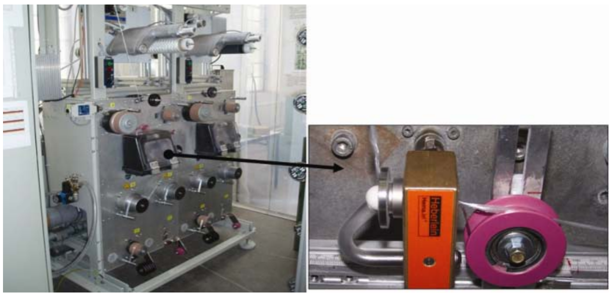


Fig. 1 Air-jet texturizing machine utilized for commingled yarn production (left) and detail view of the air nozzle (right)

Over-delivery of input yarns is necessary for the formation of the commingled structure [12]. This indicates the possibility of slightly twisting the commingled yarn to create a more compact yarn structure without causing significant effect on the composite properties. In the literature, contributions about the effects of twisting on high performance yarns were reported. However, no study is available about the effect of twisting on the commingled yarns and their composites. Within the scope of this study, main aim is to determine whether twisting can be applied to commingled yarns in order to improve the processing behavior on textile machinery. The effect of twisting level both on the yarn and composite properties were analyzed to see how the physical and mechanical properties were changed.

II. EXPERIMENTAL

A. Materials

The GF/PP commingled yarns were produced with the commercial input materials of 300 tex glass (E 35, P-D Glasseiden GmbH, Germany) and 3 x 32 tex polypropylene (Prolen H, CHEMOSVIT FIBROCHEM a.s., Slovakia) which resulted in a fiber volume fraction of 52% in UD composites. Commingled yarns were produced with 4 bar air pressure in the nozzle and a winding speed of 100 m/min. In order to generate the commingled structure, input cylinders deliver the glass and polypropylene yarns with a higher speed than the output cylinder which is removing the final commingled yarn out of the air-nozzle. This setting is called over-delivery and defined as the percentage ratio of the speed difference to the output cylinder speed. Equation 1 shows the calculation of over-delivery OD, where S_i is the input speed of feeding cylinders and S_o is the output speed of take-up cylinders.

$$OD = \frac{S_i - S_o}{S_o} * 100 \tag{1}$$

Over-delivery of glass yarns was kept at a value of 2% to avoid damage and extensive loss of orientation. Over-delivery of polypropylene yarns was 8%, therefore polypropylene filaments had higher entanglement than glass filaments and were tending to be at the outer part in the cross-section.

Produced commingled yarns were twisted (DirecTwist, Agteks) with 0, 5, 10, 15, 20, 40 and 60 tpm (twist per meter) and compared with the reference yarn which was commingled without any further process. 0 twist per meter in the trials actually means winding to another bobbin by using the same twisting machine. Winding without twist was done to isolate the effect of extra processing on the yarn properties. 5 to 20 tpm were the main experiments of concern whereas 40 and 60 tpm experiments demonstrated extreme values. Uni-directional (UD) composites were produced with compression molding. Processing conditions for compression molding is shown in Figure 2.

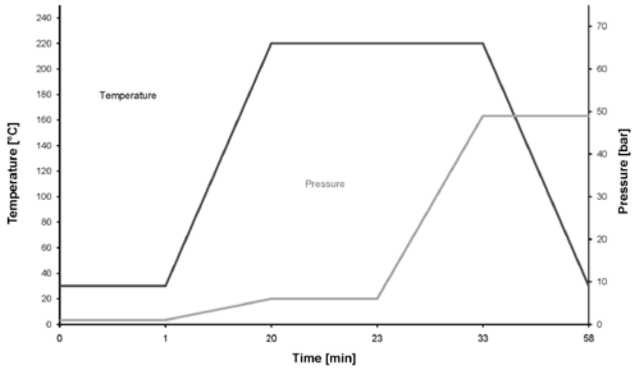


Fig. 2 Processing parameters for compression molding of UD-composite plates

Woven fabrics with the below defined weave were produced with weft densities of 7, 8, 9 and 10 yarn/cm. Warp density was 20 yarn/cm for every sample. Commingled hybrid yarns, which were defined in Section 4, were used both as warp and weft yarns. Compression molding technique was used with the same settings of Section 4. In order to increase the wall thickness of spacer fabrics, it is possible to lay flat woven fabrics above and under the spacer fabrics, and they can be pressed together. Therefore, within the design of experiments, 1, 2 and 3 layers of flat woven fabrics were consolidated and tested.

B. Testing Procedure

Yarn profiles as well as yarn-yarn and yarn-metal friction coefficients were determined by using dynamic tensile tester (LH-402 CTT-DTT Attachment, Lawson Hemphill Inc. USA). A CCD camera was used to measure the yarn diameter values with 3.25 micron precision when the yarn was moving at a speed of 100 m/min. Yarn-metal and yarn-yarn friction coefficients were determined dynamically according to ASTM D-3108, and ASTM D-3412. Tensile tests for yarns were executed with 20 specimens according to the norm DIN EN ISO 2062, with a clamping length of 500 mm and testing speed of 25 mm/min (Z100, Zwick GmbH & Co. KG). Tensile tests of UD-composites were executed according to DIN EN ISO 527-4. Upper and lower clamping areas were 50 mm each, and the testing lengths of the specimens were 150 mm. 0° specimens had a width of 15 mm and 90° specimens had a width of 25 mm. 12 specimens for 0° and 8 specimens for 90° were tested for each twisting level and the reference. Testing speeds for both 0° and 90° were 2 mm/min. Confidence intervals with 95% were determined according to Student's t-distribution.

Woven fabrics were tested according to DIN EN ISO 13934-1, with a width of 50 mm and gauge lengths of 200 mm. 5 samples were tested for each trial. For the woven composites, tensile tests were executed according to DIN EN ISO 527-4. Upper and lower clamping areas were 50 mm each, and the testing lengths of the specimens were 150 mm. Both weft and warp direction samples had the width of 25 mm. Testing speed were 2 mm/min. 4 point bending tests were executed according to DIN EN ISO 14125. Sample length was 60 mm and sample width was 15 mm. Testing speed of bending was 2 mm/min. Charpy impact test was executed according to ISO 179-2. Confidence intervals with 95% were determined according to Student's t-distribution.

III. RESULTS AND DISCUSSION

A. Commingled Yarn Structure

Commingling process is based on the mixing of materials through an air nozzle. As in the air jet texturizing process, commingling process creates a special yarn structure with two different areas which are called as bulky and knot areas (Fig. 3). Continuous air pressure through the nozzle creates distinctive areas; in bulky region the materials are voluminous and open whereas in knot areas they are intermingled together. Various process parameters such as nozzle type, air pressure, take-up speed etc. affect the frequency and intermingling intensity of knot areas. However, a full control on this phenomenon is not possible. In the case of commingled yarns, a better mixture of reinforcement and matrix materials occurred in the knot area. Figure 3 demonstrates the cross-sectional observations from bulky and knot areas, dark points are polypropylene and the light colored points are glass filaments.

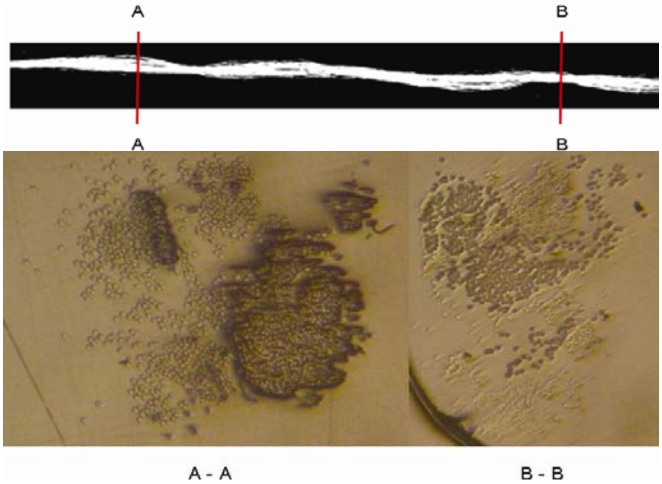


Fig. 3 Cross-sectional observations of bulky (A-A) and knot (B-B) areas of GF/PP commingled yarns X-twill weave (left) L: lower weft yarn, U: upper weft yarn, and woven fabric (right)

Profile scanning results demonstrated a progressive improvement of commingled yarn evenness with increasing twist (Fig. 4). Bulky and sticky regions on commingled yarns were the main cause of production stops during weaving. The number of events, which is defined as ±50% variations in yarn diameter, was decreased from 42 events/m to the interval of 30-35 events/m for all twisting ratios.

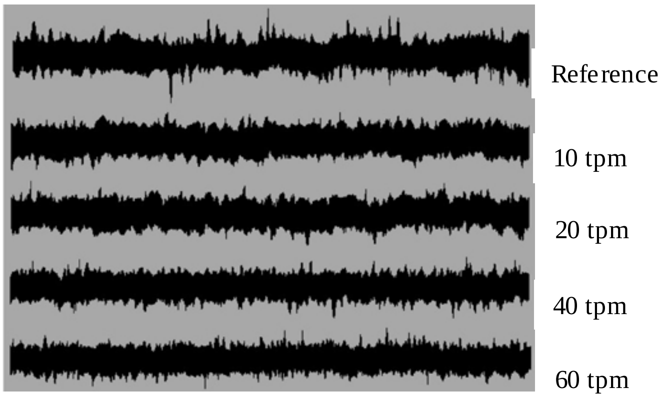


Fig. 4 Comparison of GF/PP commingled yarn profile, from top to bottom; reference commingled yarn, 10tpm, 20tpm, 40tpm, 60tpm

Mean values of yarn diameter (Fig. 5) were increased for 0 tpm and 5 tpm samples, which was caused by the effect of the additional process step. After 10 tpm, yarn diameter decreased gradually.

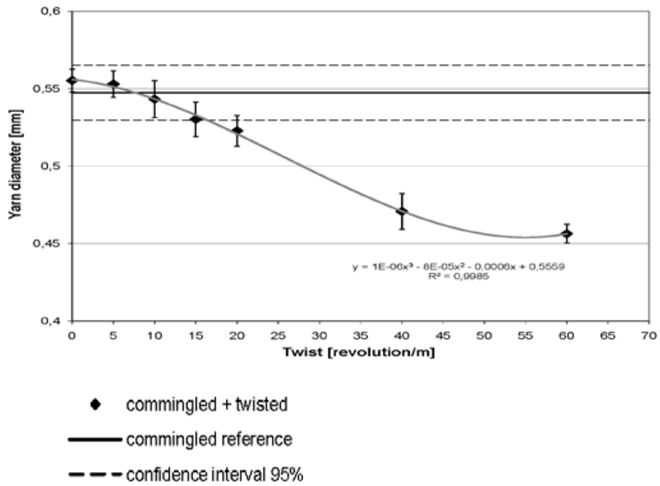


Fig. 5 Comparison of GF/PP commingled yarn profile, from top to bottom; reference commingled yarn, 10 tpm, 20 tpm, 40 tpm, 60 tpm

The standard deviation of every sample was less than the reference commingled yarn, thus more regular yarn structure was generated.

Small yarn diameters enable denser packing of material during weaving. 3rd degree regression polynomial in Figure 3 has a local minimum around 55 tpm. After 60 tpm the diameter would not change significantly. However, the regression polynomial increases. Therefore the regression polynomial can be used for interpolation between the twisting values of 0 tpm and 60 tpm, but twisting values more than 60 tpm cannot be estimated with extrapolation.

B. Yarn Mechanical Properties

Over-delivery of input materials in commingling process is necessary in order to create the knot areas, and most of the additional material length is integrated in these areas because the bulky region can easily be stretched during further processing. The twist angle equivalent of over-delivery ratio was calculated according to Equation 2, where α_{od} is twist angle equivalent caused by over-delivery and OD (%) is the over-delivery of input material.

Over-delivery of the reinforcement material within commingled hybrid yarn can be approximated as an angle distortion of a lamina. The input length of the reinforcement material is the hypotenuse of a right triangle and the output length is the adjacent side. Figure 6 demonstrates this approximation where OD is the over-delivery as percentage and θ is the angle of distortion.

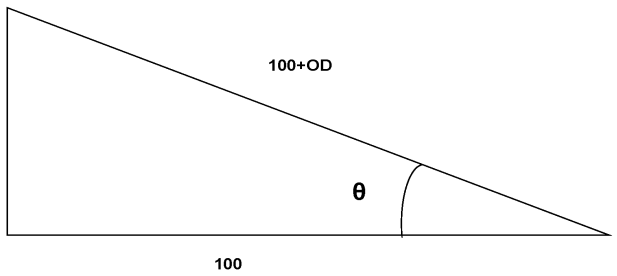
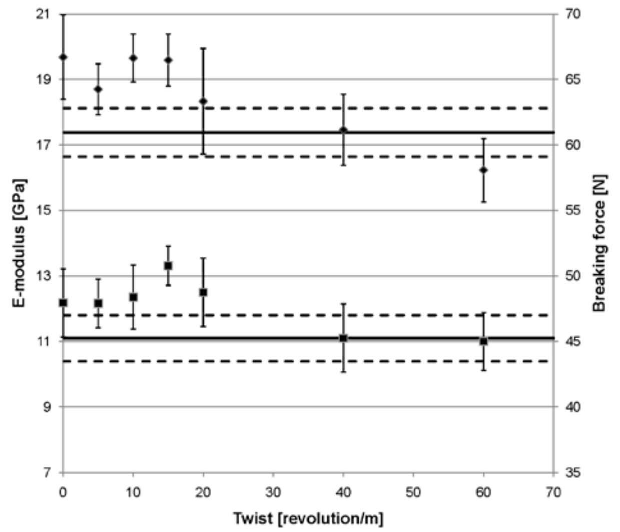


Fig. 6 Comparison of GF/PP commingled yarn profile, from top to bottom; reference commingled yarn, 10tpm, 20tpm, 40tpm, 60tpm

The inverse trigonometric function of cosine gives the equivalent of the distortion angle as shown in the Equation 2.

$$\alpha_{od} = \cos^{-1}\left(\frac{100}{100+OD}\right) \tag{2}$$

An interesting phenomenon was the increase of both breaking force and E-modulus of commingled yarns after further processing. After twisting with 0° (only winding), yarn samples had higher E-modulus and breaking force than the reference yarn (Fig. 7). This is caused by the restructuring of the knot areas under tension, the yarn was stretched and the orientation of the reinforcement material in knot areas was increased. Figure 7 demonstrates the E-modulus and breaking force comparison of twisted and reference GF/PP commingled yarns. 40 tpm sample had almost the same E-modulus and breaking force values as the reference sample. Reduction of E-modulus started with 60 tpm sample, however the breaking force was still the same as the reference yarn. These results indicate that the higher intermingling of filaments through twisting increases the mechanical properties of commingled yarns. Damage on glass fibers cannot be easily detected with yarn testing.



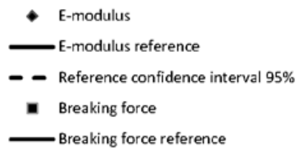


Fig. 7 Effect of twisting on the E-modulus and breaking force of GF/PP commingled yarns

C. UD Composite Properties

The 0° and 90° E-modulus calculations were executed according to laminate theory. UD-composite calculations were based on the homogeneous distribution of the glass filament in the PP matrix. Off-axis angle equivalent of over-delivery value for glass yarn was integrated to the equation, thus the UD composites structures were assumed to have a slight angle distortion.

Slab models deliver sufficient approximation to the elastic constants of a lamina. Within this model, aligned long fiber composites were treated as if the two constituents of matrix and reinforcement are bonded together. Relative thicknesses of slabs were determined according to the volume fractions of fiber and matrix. Interface regions as well as local stress concentrations were ignored. E1 (E-modulus fiber direction) is calculated according to equal strain assumption for both matrix and fiber in longitudinal direction. The Equation 3 is also called as "the rule of mixtures" and delivers a very good approximation. Discrepancies may result from the different poisson's ratios of matrix and reinforcement. However, it can be theoretically proved by the Eshelby model that the deviation is small under all conditions [13], [14].

$$E_1 = E_{1f} * Vf + E_m * (1-Vf) \tag{3}$$

Transverse modulus of a composite with unidirectional fibers can also be approximated by a slab model which assumes an equal stress condition for matrix and fibers. The stress field is complex under transverse loading and in the literature, especially for thermoplastic matrices, underestimation of transverse modulus was reported. The modified equation for the transverse modulus contains a correction factor η [15]-[17]. If η is taken as 1, the equation becomes the usual expression derived from an equal stress assumption for matrix and reinforcement. In order to fit the experimental data, η was taken as 0.6 which compensates the above mentioned underestimation of transverse modulus.

$$E_2 = \frac{Vf + \eta * (1-Vf)}{\dfrac{Vf}{E_{2f}} + \dfrac{\eta * (1-Vf)}{E_m}} \tag{4}$$

The expression for the in-plane shear modulus is analogous to the expression of transverse modulus because it assumes equal shear stress on the matrix and fibers. In order to avoid the underestimation, η's parameter with 0.6 is applied in the calculations.

$$G_{12} = \frac{Vf + \eta' * (1-Vf)}{\dfrac{Vf}{G_{12f}} + \dfrac{\eta' * (1-Vf)}{G_m}} \tag{5}$$

Since the equal strain assumption is applicable to a UD lamina, the poisson's ratio can be determined by "the rule of mixtures".

$$\nu_{12} = \nu_{12f} * Vf + \nu_m * (1 - Vf) \tag{6}$$

According to the above expression, 2% over-delivery of glass filaments was equivalent to 11.36° off-axis angle distortion. The off-axis longitudinal and transverse stiffness were calculated according to laminate theory.

Stiffness value in longitudinal direction is found as 34.13 GPa which is underestimating the experimental results. Experimental results of longitudinal E-modulus in Figure 8 show agreement with the nominal values stiffness values according to the rule of mixtures. This indicates that the angle distortion caused by the over-delivery disappears during compression molding under tension. Modulus of elasticity in 0° direction is not much affected from twisting. Statistically, only the modulus of elasticity of the 60 tpm sample can be regarded as a reduction. On the other hand, the effect of further processing can be easily seen from the tensile strength reduction starting immediately with 0 tpm sample. All the samples had an overall tendency of strength reduction. However, between 0 tpm and 60 tpm samples, it cannot be concluded that higher twist reduces the strength more than lower twist.

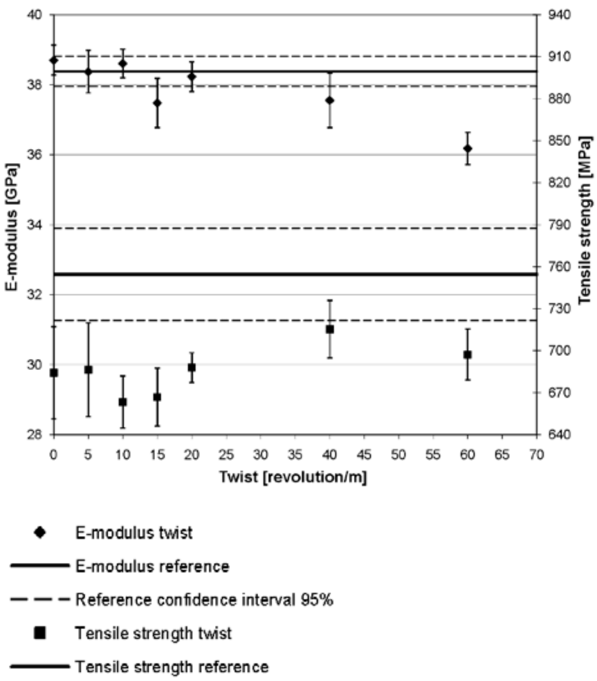


Fig. 8 Modulus of elasticity and tensile strength of UD composites from GF/PP commingled yarns in 0°

Lamina stiffness calculation in transverse direction, 3.98 GPa, is in good agreement with overall experimental results (Fig. 9). It can be seen in Figure 5 that the yarn diameter is decreasing after 10 tpm. As the UD performs were prepared with the same amount of material, increasing compactness of the reinforcement material leads to greater resin rich areas. This reduces the E-modulus in transverse direction. Transverse tensile strength shows a slight reduction tendency with increasing twist level.

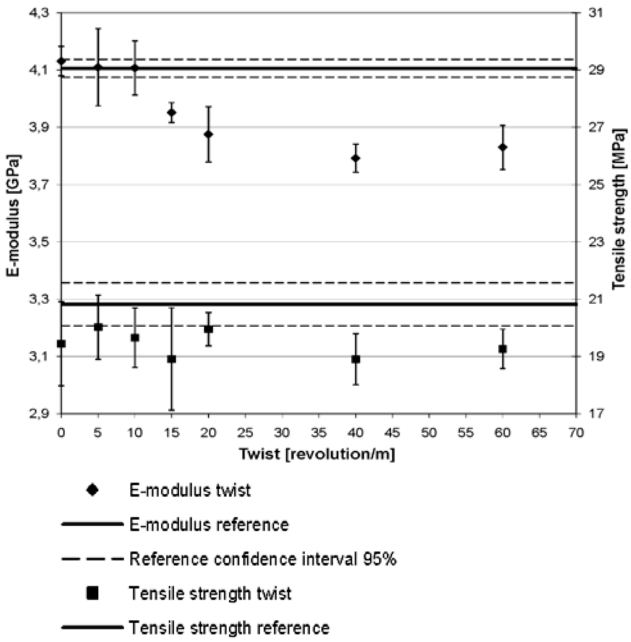


Fig. 9 Modulus of elasticity and tensile strength of UD composites from GF/PP commingled yarns in 90°

D. Woven Fabric Properties

It is important to execute experiments concerning the mechanical characteristics of 2D woven fabrics and their composites in order to gain insight about the potential performance of composites from 3D woven fabrics. The aim of this section is to determine the process damage on the reinforcement material as well as the effect of structural parameter in particular weft density and number of plies.

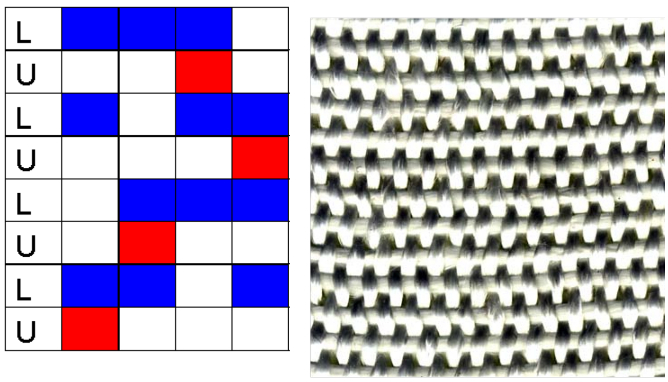


Fig. 10 X-twill weave (left) L: lower weft yarn, U: upper weft yarn, and woven fabric (right)

Compression molding causes significant change of thickness during consolidation of thermoplastic matrix preforms. If a constant weave is selected, increasing the weft density results in higher weight per unit area as well as a higher thickness of the final composite. On the other hand, higher weft density changes the inner structure of the woven fabric and processing conditions. A weaving machine with a dobby shed opening mechanism has a limited number of heddle frames (mostly up to 24). The weaving machine, which was used for the development of spacer fabrics, had 16 heddle frames. Spacer fabrics with woven cross-links have four different areas, two for upper and lower layers and two for the cross-links [18]. These four areas have four heddle

frames each for the construction of weave. Figure 10 demonstrates the selected double layer X-twill weave for the woven areas of spacer fabrics. Double layer woven fabric provides sufficient thickness after compression molding, and the X-twill weave is homogenous due to its both diagonal directions. Usual twill weaves have only one diagonal direction which results in anisotropic in-plane mechanical properties.

Fabric mass per unit area increases with the increase of weft density. Table 1 demonstrates the variation of mass per unit area for the woven fabric samples with 7-10 yarn/cm. This increase directly affects the final composite thickness which is shown in Table 2.

TABLE I RELATION BETWEEN WEFT DENSITY AND MASS PER UNIT AREA

Weft Density [Yarn/Cm]	**7**	**8**	**9**	**10**
Mass per unit area [g/dm²]	11, 307	11, 960	12, 389	13, 065

TABLE II THICKNESSES OF CONSOLIDATED WOVEN FABRICS

		Weft Density [number of yarns/cm]			
		7	8	9	10
Number of Layers	1	0,68 mm	0,71 mm	0,73 mm	0,77 mm
	2	1,36 mm	1,4 mm	1,46 mm	1,53 mm
	3	2,03 mm	2,1 mm	2,19 mm	2,28 mm

Changing of process parameters on the weaving machine also changes the amount of damage on the materials. Process damage on the materials during weaving is mainly caused by friction through feeding, shear and bending caused by the heddle frames, shear stresses caused by beat-up and the friction and buckling caused by the take-up motion. Conventional materials such as cotton compensate these stresses with their internal elongation. Reinforcement materials such as glass fibers are mostly brittle and they are prone to damage particularly under bending along a small radius. In this sense, heddle frames are the most critical machine elements where process damage occurs. Changing of weft density also changes the flow rate of material, thus higher weft density results in higher number of cycles of warp yarns through the heddle frames. Figure 11 depicts the schematic of shed opening.

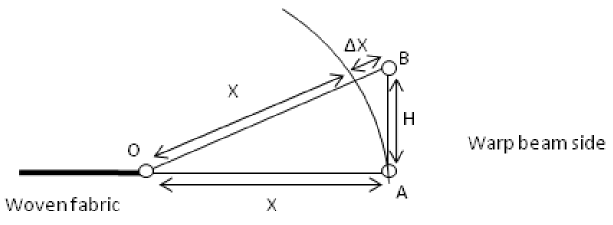


Fig. 11 Schematic of shed opening

The elongation of technical yarns is negligible, so the position change of eyelet from Point A to Point B is compensated from the warp beam side. Any point on the warp yarn must travel the distance ΔX through the eyelet of heddle frame. Weft density determines the number of cycles, in which the warp yarn can pass through this distance under buckling and shear stresses. ΔX can be calculated according to the Equation 7 where X is the distance between the woven fabric line and the horizontal position of eyelet, and H is the distance between the horizontal position and the maximum height of eyelet.

$$\Delta X = \sqrt{X^2 + H^2} - X \tag{7}$$

In every cycle of the weaving machine, warp yarns travel the distance TD which is the inverse of weft density WD (Equation 8).

$$TD = WD^{-1} \tag{8}$$

In order to find the number of cycles NC for warp yarns to pass through the heddle frames, the expression of ΔX is divided by the travel distance in one cycle TD which gives:

$$NC = \left\lfloor \sqrt{X^2 + H^2} - X \right\rfloor * WD \tag{9}$$

From Equation 9, it can be seen that the number of cycles to pass through the heddle frame is directly proportional to the weft density. Therefore it is expected to have higher damage to the warp yarns processed with higher weft densities.

Figure 12 compares the breaking force of unprocessed reference GF/PP commingled yarns and the processes steps after warp beam preparation and the woven fabric manufacturing with different weft densities. As expected, the tendency of reduction in breaking force can clearly be seen both on the weft and the warp yarns.

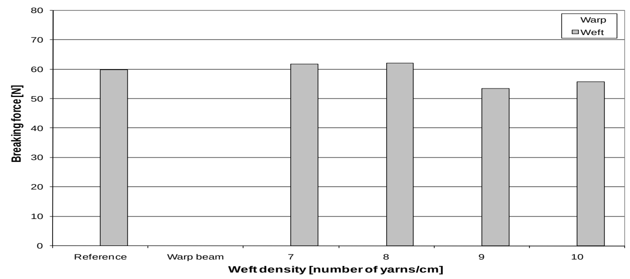


Fig. 12 Change of yarn tensile strength after beaming and weaving

Woven fabric tensile test results are depicted in Figure 13. The tendency of breaking force reduction of fabrics in warp direction with increasing weft density is higher in comparison with the tendency of individual yarns. The reason for this phenomenon is that both warp yarn crimp and damage to the yarn increases with higher weft density. In weft direction, breaking force increases with higher weft density simply due to the increased number of yarns. Therefore the process damage cannot be seen directly from the breaking force of the fabric.

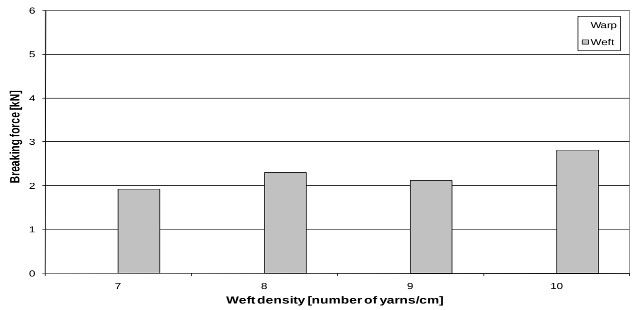


Fig. 13 Tensile strength of woven fabrics with different weft densities

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Compression molding causes extensive deformation of woven fabrics in the normal direction. Depending on the process conditions and the fabric structure, the thickness of the final composite is around 20% of the thickness of woven fabric. This deformation in the normal direction results in the sinus form of warp yarns, which can be seen in Figure 14 for different weft densities. It can be clearly seen from the figure that the increasing weft density also increases the lateral deformation. Thus the period of sinus form in the sample with the weft density of 10 yarn/cm is shorter than that of the sample with the weft density of 7 yarn/cm.

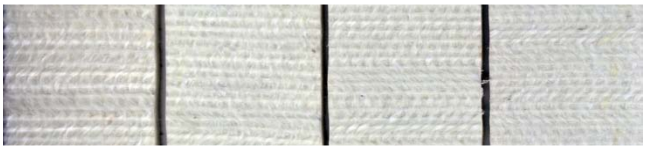

Fig. 14 Composite surfaces with weft densities of 7 to 10 from left to right

Figures 15–20 demonstrate the results of tensile tests in warp and weft directions with weft densities 7-10 and 1-3 plies. Increasing weft density slightly increases both modulus of elasticity and tensile strength in weft direction. Higher weft density changes the structure of the reinforcement, particularly the curvature of warp yarns along the weft yarns increases. Higher curvature of warp yarns results in smaller resin rich areas which have a positive effect on tensile behavior. On the other hand, higher weft density reduces the modulus of elasticity and tensile strength drastically. Process damage on the warp yarns is higher with higher weft density (Figures 12), but the reduction of properties is mainly caused by the distortion of the reinforcement material.

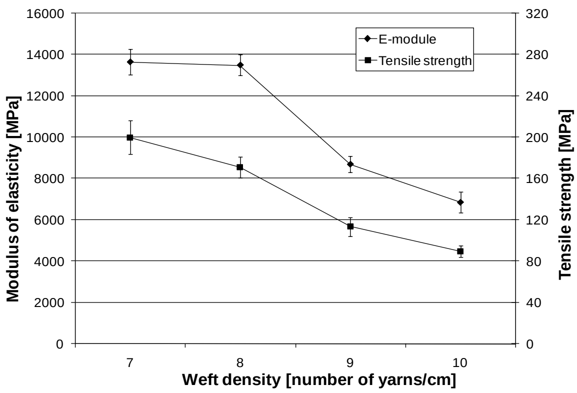

Fig. 15 Modulus and tensile strength of 1 layer consolidated fabrics in warp direction

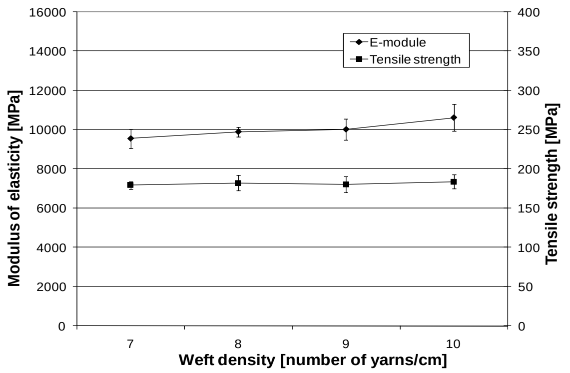

Fig. 16 Modulus and tensile strength of 1 layer consolidated fabrics in weft direction

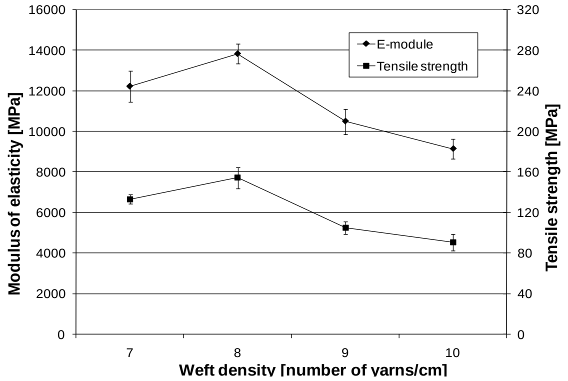

Fig. 17 Modulus and tensile strength of 2 layer consolidated fabrics in warp direction

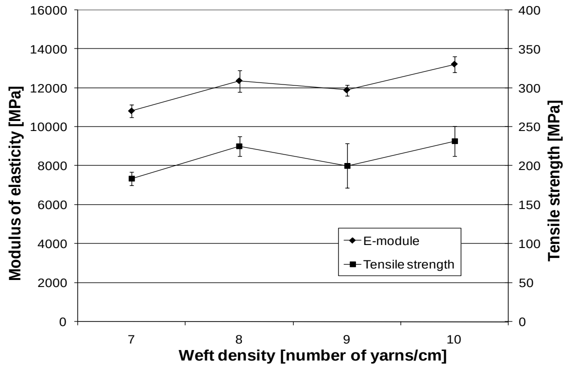

Fig. 18 Modulus and tensile strength of 2 layer consolidated fabrics in weft direction

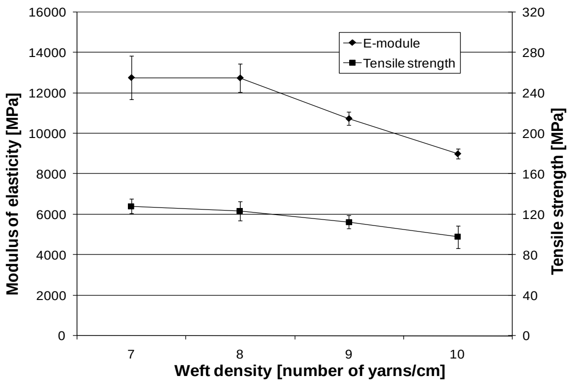

Fig. 19 Modulus and tensile strength of 3 layer consolidated fabrics in warp direction

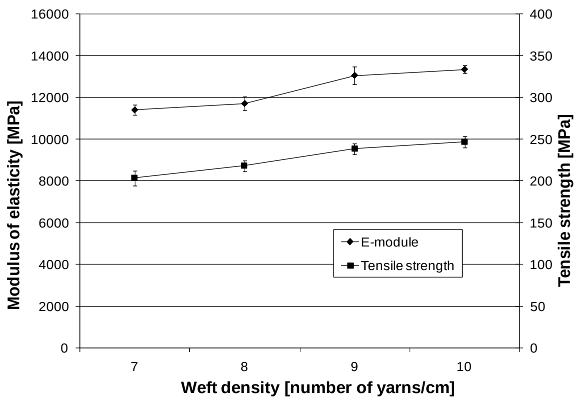

Fig. 20 Modulus and tensile strength of 3 layer consolidated fabrics in weft direction

Bending and impact tests were conducted with two and three layers consolidated woven fabrics. One layer fabrics did not have the sufficient thickness. Flexural strength increases with increasing weft density in the weft direction. However, flexural strength reduces with increasing weft density in the warp direction (Figure 21). Impact strength is mostly affected by the thickness of the samples. Therefore, increasing of weft density and the number of plies increase the total impact energy (Figure 22)

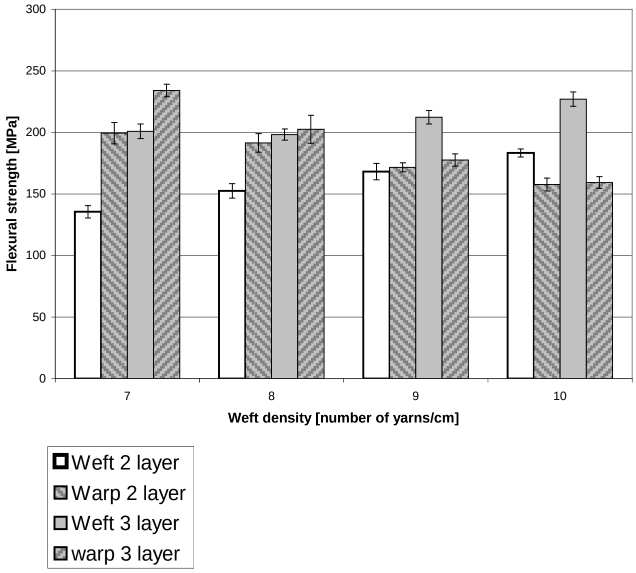

Fig. 21 Flexural strength of 2 and 3 layer consolidated fabrics in warp and weft direction

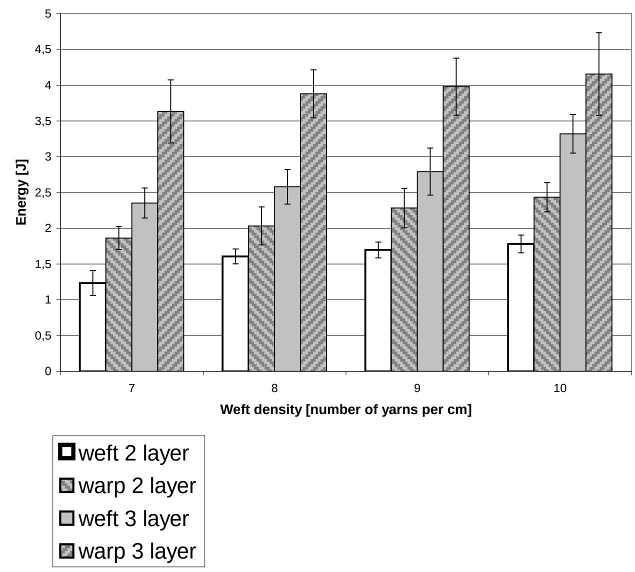

Fig. 22 Impact strength of 2 and 3 layer consolidated fabrics in warp and weft direction

IV. CONCLUSION

Effects of twisting on the mechanical properties of GF/PP commingled yarns are analyzed. This study is initiated through the production stops caused by the open and sticky commingled yarn structure during weaving of dense 3D woven preforms. Twisting decreases the average yarn diameter and creates a more compact and even structure. In commingled yarns, two distinctive areas can be recognized. These areas have varied mixing quality and yarn consumption. Increases of both E-modulus and tensile strength of commingled yarns are observed until 40 tpm. A statistically confident reduction of E-modulus was observed after 40 tpm. However, UD tensile strength values of twisted samples were around 10% less than the reference commingled yarn. E-module in transverse direction starts decreasing with 20 tpm which correlates with the reduction in yarn diameter. A slight decrease in transverse tensile strength was observed. Twist application on commingled yarns creates more compact yarn structure which can increase productivity in dense woven preform manufacturing. Up to 20 tpm twist levels can be applied where a longitudinal strength reduction of about 10% can be tolerated without any E-modulus reduction. Similar to the investigations of Naik and Kuchibhotla [19] about the twist of glass yarns, the yarn twist does not significantly affect the composite properties up to an optimum twist angle. The influence of the compaction of the yarns by twisting the weavability was not discussed.

Woven fabrics with commingled yarns are subject to extensive deformation in the out-of plane direction when manufactured by hot press molding. Higher weft density increases the final composite thickness. However, it also increases the crimp of warp yarns, thus reduces the in-plane mechanical properties. Increasing weft density increased the damage both on weft and warp yarns. Single, double and triple layers of separate woven fabrics were pressed and consolidated with four different weft densities. In warp direction, significant decrease of modulus and strength was observed mainly due to the increasing crimp of internal structure. In weft direction, a slight increase of modulus and strength with increasing weft density was observed which was caused by the compact reinforcement structure and the reduced resin rich areas.

According to these results, higher crimp which was caused by higher weft density reduces the tensile properties significantly. Therefore, the yarn crimp should be avoided inside the woven structure. It is advantageous for tensile properties to adjust the component thickness by multiple layers of woven fabrics with lower weft density instead of using fewer layers of woven fabrics with higher weft density.

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